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Spectrodirectional remote sensing: From pixels to processes

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Abstract

This paper discusses the historical evolution of imaging spectroscopy in Earth observation as well as directional (or multiangular) research leading to current achievements in spectrodirectional remote sensing. It elaborates on the evolution from two separate research areas into a common approach to quantify the interaction of light with the Earth surface. The contribution of spectrodirectional remote sensing towards an improved understanding of the Earth System is given by discussing the benefits of converging from individual pixel analysis to process models in the land-biosphere domain. The paper concludes with an outlook of research focus and upcoming areas of interest emphasizing towards multidisciplinary approaches using integrated system solutions based on remote and in situ sensing, data assimilation, and state space estimation algorithms.

Keywords: Imaging spectroscopy; Imaging spectrometry; Directional; Multiangular; Remote sensing; Land-biosphere models

1. Introduction

This manuscript is reprinted in modified form of the original address given by the author on the 7th October 2004 on the occasion of his accession to the post of professor of geo-information science with special emphasis on remote sensing at Wageningen University.

1.1. Brief history of spectroscopy

About 300 years ago, in 1704, Sir Isaac Newton published in his 'Treatise of Light' (Newton, 1704) the concept of dispersion of light (cf., Fig. 1). He demonstrated that white light could be split up into component colours by means of a prism, and found that each pure colour is characterized by a specific refrangibility. The corpuscular theory by Newton was gradually successed over time by the wave theory. Consequently, the substantial summary of past experiences performed by Maxwell (1873), resulted in his equations of electromagnetic waves. But it was not before the 19th century, until the *quantitative* measurement of dispersed light was recognized and standardized. A major contribution was Fraunhofer's discovery of the dark lines in the solar spectrum (Fraunhofer, 1817); and their interpretation as absorption lines on the basis of experiments by Bunsen and Kirchhoff (1863). The term spectroscopy was first used in the late 19th century and provides the empirical foundations for atomic and molecular physics (Born and Wolf, 1999). Significant achievements in imaging spectroscopy are attributed to airborne instruments, particularly arising in the early 1980s and 1990s (Goetz et al., 1985; Gower et al., 1987; Green et al., 1998; Kruse et al., 1990; Rowlands et al., 1994; Vane et al., 1984, 1993). However, it was not before 1999 until the first launch of an imaging spectrometer in space (e.g., NASA Moderate Resolution Imaging Spectrometer (MODIS); http://modis.gsfc.nasa.gov/). However, scientific terminology and definitions evolve over time. Presently, an imaging spectrometer is usually

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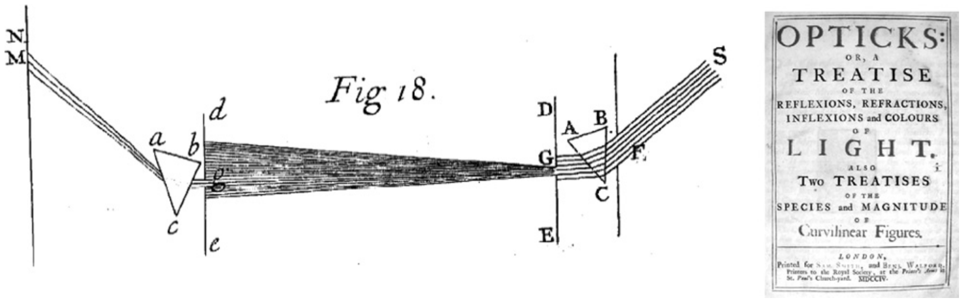

Fig. 1. Newton's drawing of the dispersion of light published in his treatise of light (Burndy-Library, 2005; Newton, 1704).

not any longer defined by a total minimum number of spectral bands (earlier, >10 spectral bands was a justification to use the term imaging spectrometer), rather than by a contiguous (or redundancy) statement.

1.2. Brief history of directionality

Historically, directionality developed apart from spectroscopy and it was only after Galilei (1632) had developed his mechanics, that optics was put on a firm foundation by Leonardo Da Vinci (cf., Fig. 2). Hooke (1664) discovered the presence of light in the geometrical shadow, but an earlier qualitative description exists from Leonardo Da Vinci in his notebooks, where he demonstrates using experimental methods, that 'The position of the Eye above or below [trees] varies the shadows and lights in trees' (following Richter, 1970, as cited in Lucht, 2004). Even though this was an early start for directional observations, the quantification of directionality was also only achieved in the late 19th century. Early works combining observational methods with physical definitions appear in the mid of the 20th century, lead by Minnaert (1940) and more remote sensing related work by Middleton (Middleton and Mungall, 1952). Finally, the standardisation of the geometrical nomenclature was due in the early 1970s as coined by Nicodemus (Nicodemus, 1970; Nicodemus et al., 1977). The term bidirectional reflectance distribution function – or short BRDF – originates also from that time and the directionality found subsequently its way into computer science and particular photorealistic rendering, which gave this science a large boost in the 1970s. But alike spectroscopy, it was not before 1991, until the first directional instrument on a satellite – having two view angles – was launched in space (e.g., ESA ATSR-1 on ERS-1, 1991).

1.3. Brief history of spectrodirectional remote sensing

Early concepts of acquiring directional information from natural targets were discussed already in 1958 in the

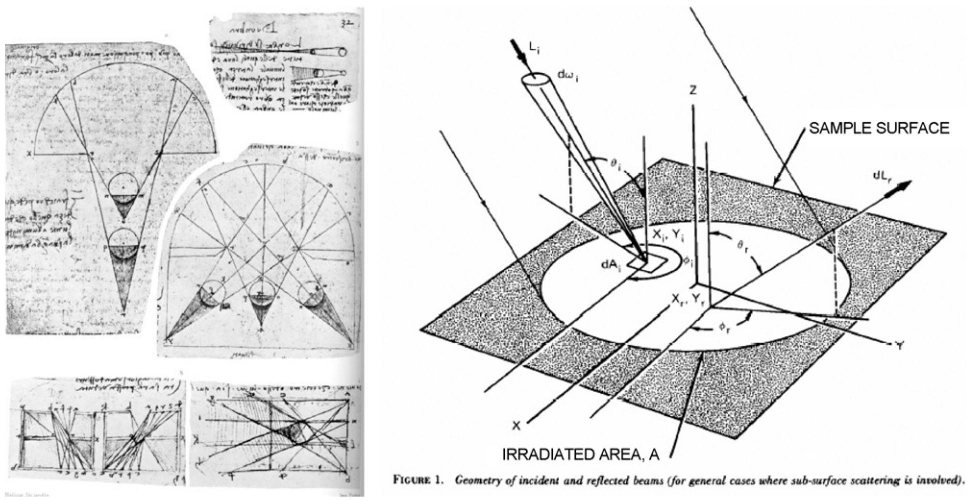

Fig. 2. Excerpt from Leonardo Da Vinci's notebook on shadows and light (Richter, 1970, left), and a conceptual drawing of Fred Nicodemus on geometrical optics in reflectance (Nicodemus et al., 1977).

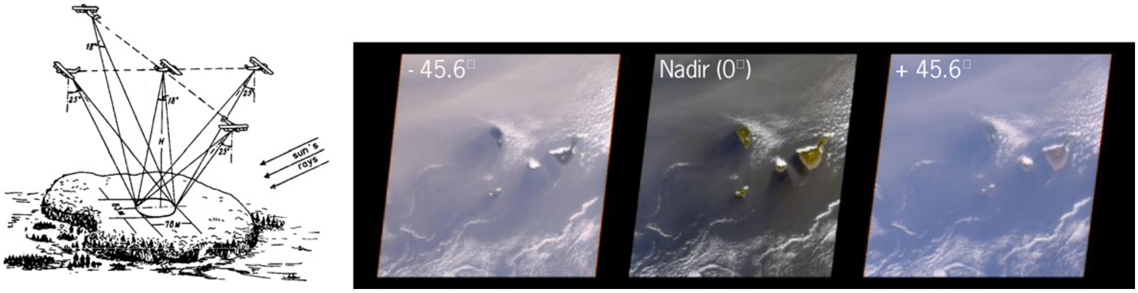

Fig. 3. Directional acquisition pattern for forest stand monitoring in 1958 (Arcybashev and Belov, 1958, left), and a 2004 NASA Terra/MISR observation in three view angles of the Canary Islands (E) ['+' denotes a forward looking, '−' a backward looking instrument] (MISR, 2005, right).

former Soviet Union (Arcybashev and Belov, 1958). The idea was to acquire a scene – a forest in this case – under various view angles by using a complex flight pattern (cf., Fig. 3). In addition, the camera – a spectrophotometer at this time – was tilted to different view directions to increase the amount of observation angles. Several satellites were launched in the 1990s to measure multiple spectral bands and view angles in various combinations (e.g., http://smsc.cnes.fr/POLDER/ CNES POLDER on ADEOS, 1996; http://www-misr.jpl.nasa.gov/ NASA MISR on TERRA, 1999). In addition, airborne instruments, partially designed as being precursor missions to future satellites (Irons et al., 1991), contributed to the wider availability of spectrodirectional data. But it was not before 2001 until a 'true' imaging spectrometer with directional capabilities was launched. The British CHRIS (Compact High Resolution Imaging Spectrometer) on board of the Belgian PROBA platform, operated by ESA (European Space Agency), can be considered as the first full spectrodirectional spaceborne instrument. However, MISR launched in 1999 is generally considered the most important contributor to the science of spectrodirectional imaging. The expression spectrodirectional is a typical finding of the 21st century. Mainly the efforts of the NASA MISR team around John Martonchik (NASA, JPL) and Michel Verstraete (JRC, It) coined this expression. Regularly the terms 'multiple view angles' or 'multiangle radiometer' – amongst others – were used before. Currently, the subject of spectrodirectional as being a combination of high spectral resolution and multiple view angles can be found regularly in literature (Baret, 2001; Strub et al., 2003), as well as sound discussions on having a combined benefit of both acquisition methods (Diner et al., 2005; Verstraete et al., 1996).

1.4. Increasing relevance of spectrodirectional and hyperspectral remote sensing

Even though the terms 'imaging spectroscopy', 'hyperspectral', and 'spectrodirectional' and resulting products have only partially found their ways into operational remote sensing services, the referencing of them as well as associated citations are exponentially increasing over the past few years (cf., Fig. 4)—a good indication of the increasing relevance of this emerging topic. The table is based on searches performed in altavista.com, citations in scopus.com using combinations of keywords (e.g., hyperspectral, imaging spectroscopy, imaging spectrometry, directional, multiangular, spectrodirectional, and variants thereof), as of September 2004.

A thematic separation of these search terms in the above overview will be increasingly difficult in the future, since methodologies used in Earth observation related *imaging* spectroscopy are now also widely used in deep space research (Clark et al., 2005), neurosciences (Devonshire et al., 2004), chemometrics (Fernández Pierna et al., 2004), amongst others.

1.5. The art of spectrodirectional science

By reassessing Leonardo Da Vinci's (Richter, 1970) and Hooke's (1664) early transition between natural

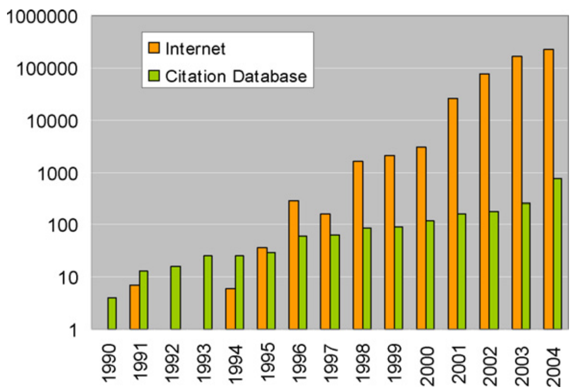

Fig. 4. Exponential growth per year of Internet and citation database-based terminology related to the terms 'imaging spectroscopy' and 'directionality'.

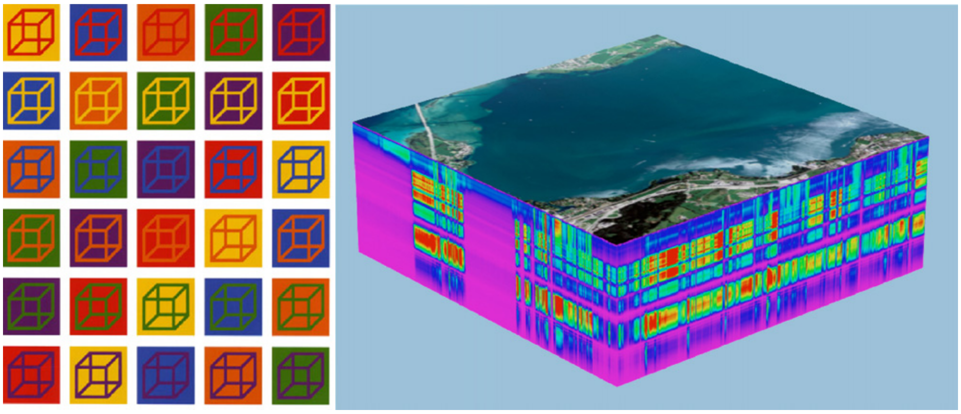

Fig. 5. ‘Cubes in Color on Color’ (by Sol LeWitt, Barbara-Krakow-Gallery, 2005, left) and imaging spectrometer data cube (Schaepman, 1999, right).

science and artistic views, these can be translated into today’s analogies.

Sol LeWitt (USA, *1928) is attributed to be a minimal artist, but states himself that his work is conceptual art. Working along his idea ‘the concept is the most important aspect of the work’, he became a synonym of a sculptor of connected open cubes in his artistic career. When he created ‘Cubes in Color on Color’ in 2003, he gave a perfect example of a conceptual definition of imaging spectroscopy (cf., Fig. 5). Spectroscopists are using these cubes with different colours to depict the two-dimensional room of the space and the third dimension indicating wavelength. When imaging spectroscopists visualize their data, usually cubes are used to express the spatial and spectral domain. Finally, an image cube can be plotted and the spectral component is coloured according to its surface reflectivity.

Paul Klee (CH, *1879, †1940) frequently used a personal sign system in his works that is abstract and figurative at the same time. His painting named ‘Ueberschach’ is therefore a perfect example to visualize the directional component of a directional data acquisition (cf., Fig. 6). The chessboard like pattern in the directional image acquisition seems to be an abstract feature of the landscape, but has its origin in different view- and illumination geometries. While flying an aircraft North–South, the scene is illuminated homogeneously. A few minutes later the same scene was recorded East–West and differences in ground reflectance are due to variation in sun–target–observer geometries.

Spectroscopy can be seen as detailing out *colours*, and when Johannes Itten (CH, *1888, †1967) – like Paul Klee a member of the Bauhaus – wrote his book ‘The Art of Color’ (Itten, 1961) it was a logical follow up that spectrodirectional models could make the best use out of these colour definitions. The similarity of Itten’s painting ‘Offenbarung’ and the visualization of a

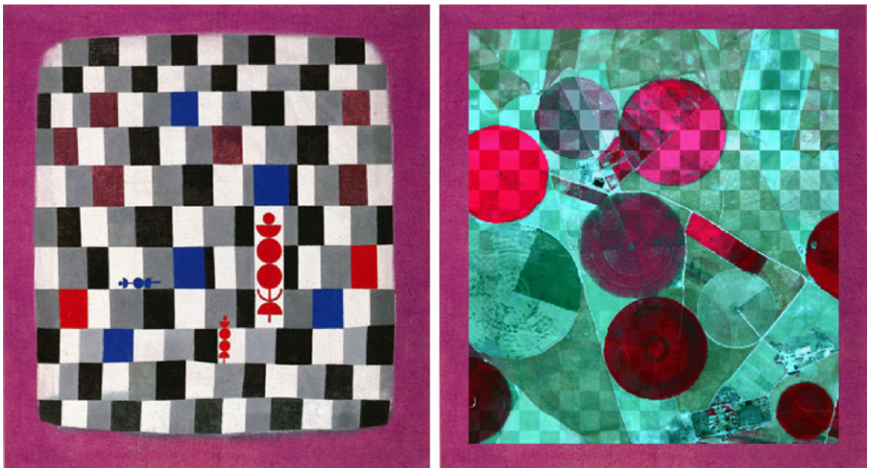

Fig. 6. ‘Ueberschach’ (by Paul Klee in 1937; Kunsthaus-Zürich, 2005, left) and directional chessboard pattern (Beisl, 2001).

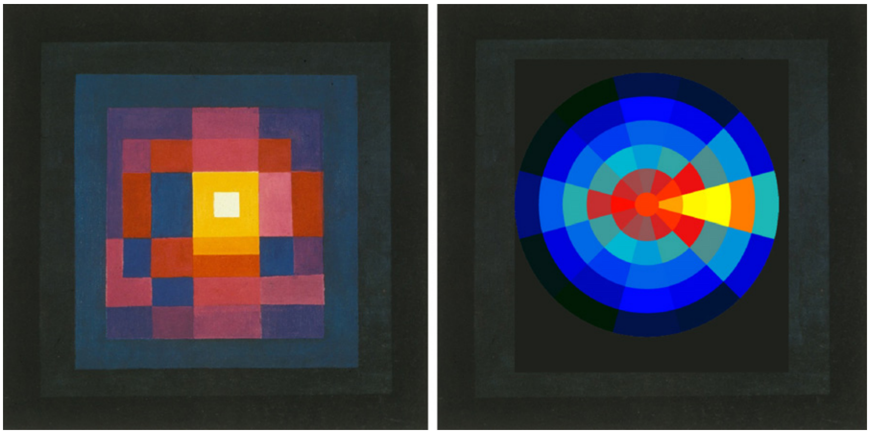

Fig. 7. ‘Offenbarung’ (by Itten, 1967, left) and results of a directional model (Dangel et al., 2005).

directional model (cf., Fig. 7) are not only analogous due to similar colour theories, but also due to a potential expression in directional illumination differences.

1.6. Spectrodirectional remote sensing—a definition

The overview of spectrodirectional imaging shall be completed by coining a definition and illustrating this definition with two different spectrodirectional acquisition concepts (cf., Fig. 8):

Spectrodirectional remote sensing is defined as being the *simultaneous* acquisition of spatially *coregistered images*, in many, *spectrally contiguous bands*, at *various observation and illumination angles*, in an internationally recognized *system of units* from a remotely operated platform.

Consequently, by applying this definition, the result will finally end in the quantitative and qualitative characterization of both, the surface and the atmosphere, using geometrically coherent spectrodirectional radiometric measurements. This result can then be used for the unambiguous direct and indirect identification of surface materials and atmospheric trace gases, the measurement of their relative concentrations, subsequently the assignment of the proportional contribution of mixed pixel signals (spectral un-mixing problem), the derivation of their spatial distribution (mapping problem), and finally their study over time (multitemporal analysis).

2. Research directions using spectrodirectional remote sensing

2.1. Introduction

The understanding of the relevance to measure biogeophysical parameters using novel techniques such as spectrodirectional remote sensing arises from various efforts in environmental policy on a global level. The often referred to Kyoto Protocol to the UN Framework

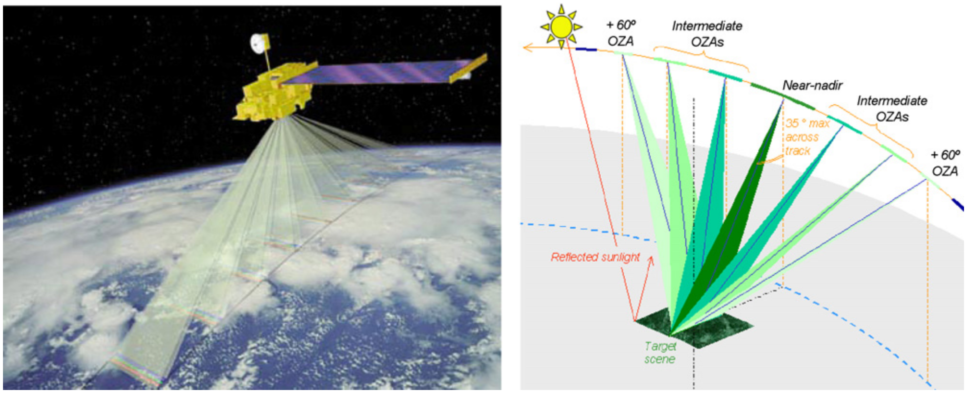

Fig. 8. Two different acquisition methods of directional information using either nine cameras pointing at different locations (left) (NASA MISR), or by using an agile platform (right) (ESA SPECTRA; SPECTRA, 2005).

convention on Climate Change (UNFCCC) proposes a global policy to be applied at international level, based on assessments of carbon emission and sequestration rates. The aim of the protocol is therefore to stabilize the CO_2 concentration in the atmosphere in the long run. In particular, the consideration of carbon sinks in the protocol has given a large momentum to implement a scientifically sound accounting and verification system. The key issues to be resolved there are the *variability*, *uncertainty*, *attribution*, *non-permanence*, *leakage*, and future *evolvement* of the carbon sequestration in the terrestrial biosphere (Valentini et al., 2000). The estimated carbon uptake of the biosphere must be consistent with all other evidence at three levels of integration of the carbon budget: *global*, *national*, *and local*.

One particular component of the Earth System, the terrestrial environment has been identified as being a critical component of the variability of the global carbon cycle. But given the natural diversity of landscapes, the (instrumented) measurement and validation approach remains challenging. Earth observation from airborne or spaceborne platforms is the only observational approach capable of providing data at the relevant scales and resolution needed to extrapolate findings of in situ (field) studies to larger areas, to document the heterogeneity of the landscape at regional scale and to connect these findings into a global view. Extrapolation can either be done by statistical and/or GIS techniques (Guisan and Zimmermann, 2000), as well as by process modelling of ecosystems. The latter is a very promising approach for testing ecological hypotheses and for assessing and forecasting the state of large landscapes up to the global scale.

Such approaches usually require the spatial input of the state of the ecosystems at simulation start and of relevant biophysical, biochemical, and/or structural information of the terrestrial ecosystems (Schaepman et al., 2003). Ecosystem models – often referred to as biogeochemistry models because they simulate pools and fluxes of relevant ecosystem elements such as carbon, nitrogen, or water – ideally combine remote sensing information on the structure of the vegetation with monthly (e.g., CENTURY (a soil organic matter agroecosystem model), see Wilson et al., 2003) to daily (e.g., BIOME-BGC (a biogeochemical cycle model), see Thornton et al., 2002) meteorological data and a set of ecophysiological parameters, which drive the processes of ecosystems. When applied to a gridded landscape, the combination of spatially explicit air- or spaceborne information on the vegetations structure with ecosystem models allow for an accurate assessment of ecosystem processes, for testing novel ecological theories and for predicting possible future states of the land surface (e.g., Kimball et al., 2000; Turner et al., 2003).

Such large scale to global quantifications are clearly beyond the realm of experimental analysis. The close coordination of Earth observation satellites and airborne instruments is thus essential for the successful validation of the contribution of the terrestrial component to the global carbon cycle (Schaepman et al., 2005b). Space agencies and international organizations have recently established a coordination mechanism (e.g., the Integrated Global Observing Strategy Partnership (IGOS-P)) that facilitates progress in space-based measurements (Rast et al., 2001).

Rast et al. (2004) outlines that the interannual variability of CO_2 fluxes is much higher for the terrestrial biosphere than for the oceans. Recent estimates suggest even that during the 1980s, 23% of the total anthropogenic carbon emissions were taken up by the oceans, and as much as 32% by the terrestrial biosphere. For the 1990s, the figures are 28% for the oceans and 34% for the land. The land-atmosphere flux represents the balance of a positive term due to land-use change and a residual terrestrial sink. The two terms cannot be separated on the basis of current atmospheric measurements. Using independent analyses to estimate the land-use change component for the 1980s based on Houghton and Hackler (2000) and Houghton et al. (1999), and the CCMLP (Carbon Cycle Model Linkage Project) (Heimann et al., 1998) the residual terrestrial sink can be inferred for the 1980s. Comparable global data on land-use changes through the 1990s are not yet available (Fig. 9).

When estimating future terrestrial carbon fluxes, the contribution of the terrestrial biosphere remains unclear, and in addition inter-model differences are still large. Simulations using Dynamic Global Vegetation Models (DGVM), consistently indicate that rising CO_2 levels are causing a persistent, later saturating carbon sink, while the effect of climate change may lead to a reduction in sink strength or even in a source (cf., Fig. 10; Rast et al., 2004).

In summary, the land-biosphere CO_2 uptake and its associated uncertainty must be understood and reduced further by performing the following actions: (i) a better determination of relevant biosphere parameters by representing the biosphere at their relevant scale in appropriate spatial and temporal scales, (ii) an enhanced (and standardized) parameterisation of the carbon exchange between vegetation, soil and atmosphere, and finally (iii) attributing the anthropogenic

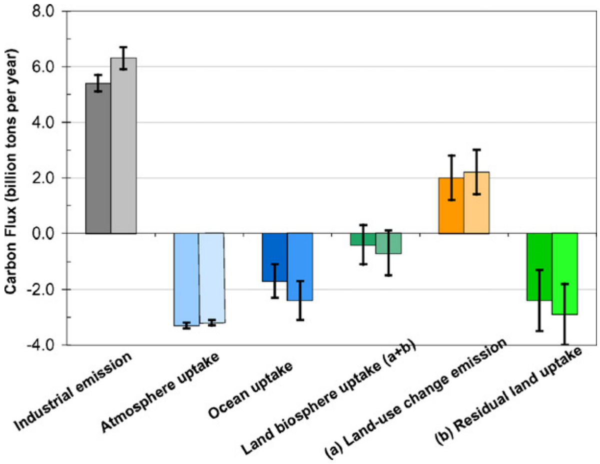

Fig. 9. Global CO_2 budgets (in PgC/year) based on intra-decadal trends in atmospheric CO_2 and O_2. Positive values are fluxes to the atmosphere; negative values represent uptake from the atmosphere. Error bars denote uncertainty (±1s), not interannual variability, which is substantially greater (visualization of Table 3.1, p. 190 from Prentice et al., 2001 in Rast et al. (2004)).

disturbance a higher importance by establishing 'vegetation scenarios' analogous to the IPCC defined 'atmospheric scenarios'.

This will allow to better estimate the evolution of the biospheric uptake, define if the biospheric sink is stable over time, and finally to resolve the question if unknown feedbacks are hidden somewhere.

2.2. The contribution of spectrodirectional remote sensing

There is little disagreement over the fact that remote sensing in general and spectrodirectional remote sensing in particular is well suited to (modified/added

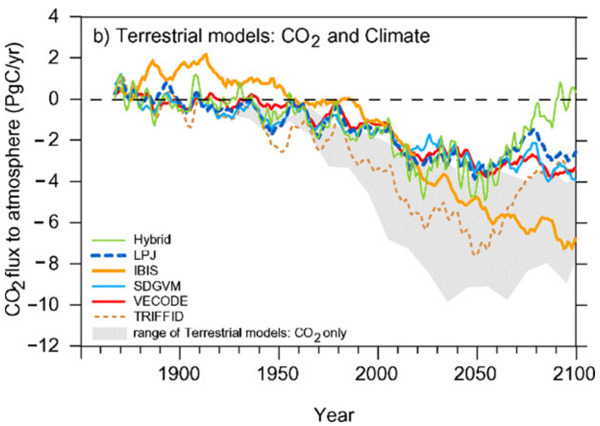

Fig. 10. Projections of the uptake of anthropogenic CO_2 by six dynamic global vegetation models driven by changes in CO_2 concentrations (IPCC, 2001).

from Cohen and Goward, 2004) map spatially distributed phenomena at various scales, such as ecosystems, habitats, plant functional groups/types, and species; measure continuous fields incorporating biophysical and biochemical variables, and map categorical variables in the form of discrete classification and land-use/cover change (LUCC). Additionally, remote sensing is suited to map temporal phenomena, in particular successional stages, map spatio-temporally coupled processes such as the phenology, and finally record disturbance induced by humans (also expressed as land-use changes), fires, volcanoes, and other extreme events.

Even though this is an important achievement, remote sensing is still confined to mostly above ground and limited penetration depth measurements. This results in the fact that approximations must be made, when assessing relevant biogeophysical and biogeochemical cycles: NPP (net primary productivity, cf., Gower et al., 1999) will always be confined to aNPP (aboveground net primary productivity) when using reflective remote sensing data. NPP is widely accepted to be GPP (gross primary production) minus the autotrophic respiration (R). However, neither NPP nor GPP can be measured directly using remote sensing and R is difficult to assess in particular in multi-species environments. Also, NPP includes components such as roots which limit remote sensing-based approaches to measure aNPP (aboveground NPP). Several definitions are documented in literature to assess aNPP, and generally it is composed of aNPP = $B + D$ (where B is the biomass increment, and D detritus or litterfall production—and significant discussion arises whether or not to include tree mortality in aNPP). The belowground NPP (bNPP) deals with the components of fine and coarse roots, as well as Mycorrhizae. Usually bNPP is considered being a calibrated fraction of aNPP, but more modern approaches include the soil-carbon balance, amongst others. Proper estimates of (global) plant growth or NPP will therefore always need significant amount of data to be assimilated or integrated to satisfy a more rigorous system (cf., Fig. 11).

The particular benefit of using spectrodirectional measurements over single view angle and limited spectral band measurements is the significant improvement of the quality and reliability of the retrievals. Spectrodirectional imaging is increasingly seen as an acquisition technology that enables biogeophysical variables of the Earth's surface to be mapped with unprecedented accuracy. Recent advances (Rast et al., 2001, 2004) document the benefit of using combined directional and spectral information showing that

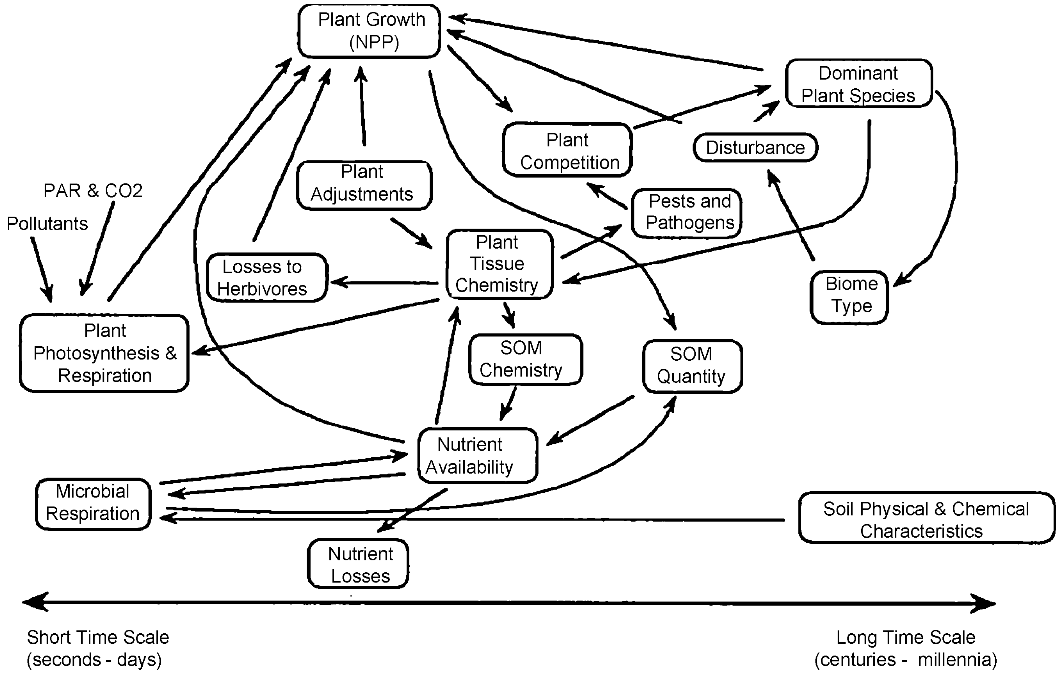

Fig. 11. Net primary productivity (NPP) estimates or plant growth listed in various scales and interactions (Field et al., 1995).

(Menenti et al., 2005) current distributed models of biosphere processes can assimilate spectrodirectional radiometric observations to improve estimates of NPP, that data assimilation does provide access to complex variables, such as soil respiration at regional scale, not easily observed with local measurements, and that directional thermal observations provide new opportunities to improve a critical element of global land-atmosphere models: the parameterization of sensible heat transfer.

Additionally, the gained knowledge of directional effects – or surface and atmospheric anisotropy – is

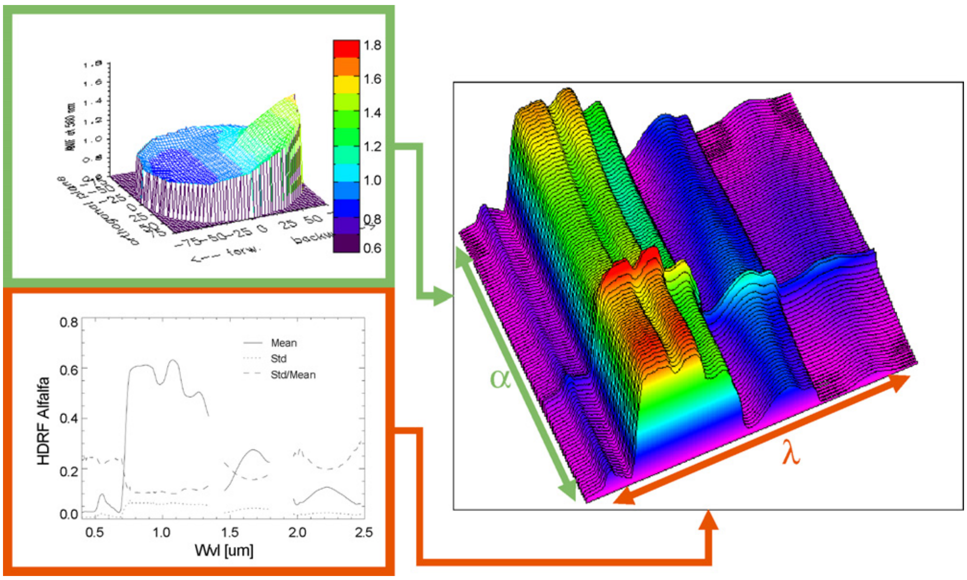

Fig. 12. Combining the spectral (left, bottom) and directional (left, top) component of remotely sensed data to achieve spectrodirectional data sets (right) (Data: Strub et al., 2003; Rast et al., 2004).

presently also being used to correct undesired effects of wide field of view angle sensors (Govaerts et al., 2004).

Concluding it can be said that the (spectro)directional remote sensing science community has two major research objectives. These are namely minimizing the influence of the anisotropic behaviour to achieve high quality, standardized and therefore comparable and reproducible data sets, as well as maximizing the information retrieval to enhance the quality and reliability of the derived products.

2.3. *From pixels to processes*

In situ measurements, individual radiance measurements, as well as satellite observations in the solar reflected domain in remote sensing are always influenced by five dimensions (the spatial, spectral, directional, temporal, and polarisation dimensions), whereas the dimension 'space' is usually a two-dimensional observation (x and y), and the direction a combination of four angles (illumination zenith and azimuth angles, as well as observation zenith and azimuth angles) having an additional dependence of object topography and orientation (e.g., upright trees growing on a slope).

Fig. 12 identifies a monotemporal in situ measurement over a homogeneous target, with neglected polarisation dependent information, reducing the dimensions to a spectral and a directional component.

Compiling literature references of documented spectral absorption features (cf., Fig. 13), one can easily estimate the potential of remote sensing to identify biochemical compounds in plants. Nevertheless, the documented features are in many cases measured using dried plant material, suggesting a potential shift of spectral features compared to fresh material, which may result in a variety of absorption lines located close to each other, and slightly offset of standard reported absorption features (Curran, 1989; Wessman et al., 1988). A major challenge remains to separate plant water content (leaf water) and columnar water vapour contained in the atmosphere due to significantly overlapping absorption lines (Sims and Gamon, 2002, 2003).

The measurement of the spatial extent using spectrometers can also vary significantly and is a crucial item when trying to integrate various spatial scales. In particular, the sampling scheme for in situ measurements plays an important role for the choice of the final application. Scaling from leaf to canopy level as well as choosing the right spatial sampling interval to characterize the landscape heterogeneity properly, is highly over-determined in remote sensing and requires trade-offs to be made to achieve the desired product accuracy. Fig. 14 illustrates the measurement of leaf optical properties at spatial scales from less than a few cm^2 up to the canopy level where usually half a m^2 is a proper measurement unit. These spatial scales ranging from leaf to canopy level can be successfully modelled using radiative transfer-based approaches (Jacquemoud et al., 2000; Pinty et al., 2001, 2004; Verhoef and Bach, 2003).

At all spatial scales, vegetation canopies and leaves are undergoing substantial dynamic behaviour, and the dynamic change of vegetation is still encapsulated with a significant uncertainty in their quantification (Cao and Woodward, 1998). By coupled analysis of spectral and

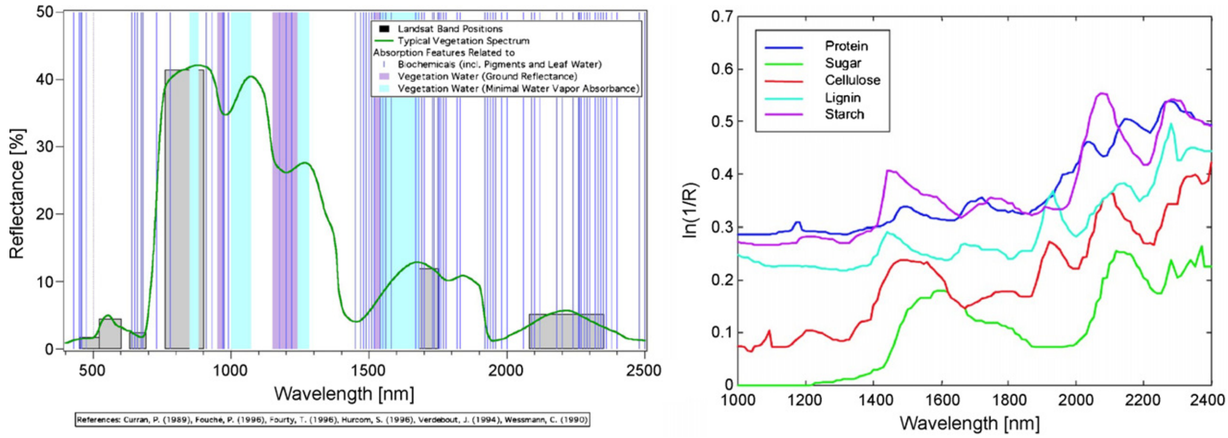

Fig. 13. Spectral features of vegetation biochemicals in the solar reflected domain: literature identified biochemical feature extraction based on spectral band position (left, Schaepman, unpublished, data compiled from Curran, 1989; Fouche, 1995; Fourty et al., 1996; Hurcom et al., 1996; Sims and Gamon, 2003; Verdebout et al., 1994; Wessman, 1990), absorption of five biochemical compounds found in leaves (right) (Wessman, 1990).

Fig. 14. Spectral measurements from leaf (needle transmission in the laboratory (left), and in vivo (middle)) to canopy level (right) (pictures by the author from the HyEco'04 campaign 2004 in the Millingerwaard (NL) and the EU MERCI project in Bily Kriz (CZ)).

temporal features, it can be demonstrated that full spectral coverage is a predominant requirement to monitor all relevant processes occurring at leaf and canopy level (Lichtenthaler et al., 1998). This is demonstrated and visualized in Fig. 15, which suggests that depending on the stress exposure time of a single leaf, different portions of the reflective part of the electromagnetic spectrum undergo more changes than others (early stress is dominating the shortwave infrared region at the beginning, whereas leaf decomposition is affecting the visible part more significantly in a later stage).

Another aspect of multitemporal analysis is the inherent measurement stability of remote sensing instruments. Significant advances have been made in measuring the radiance field with higher accuracy (Fox et al., 2003), and long-time calibration experiments demonstrate measurement stability of better than 2% uncertainty on the long run (Kneubühler et al., 2003). Fig. 16 demonstrates this using MERIS on ENVISAT as an example, and puts additional emphasis on the proper characterization of the atmosphere, including the proper choice of radiative transfer models and the solar spectrum.

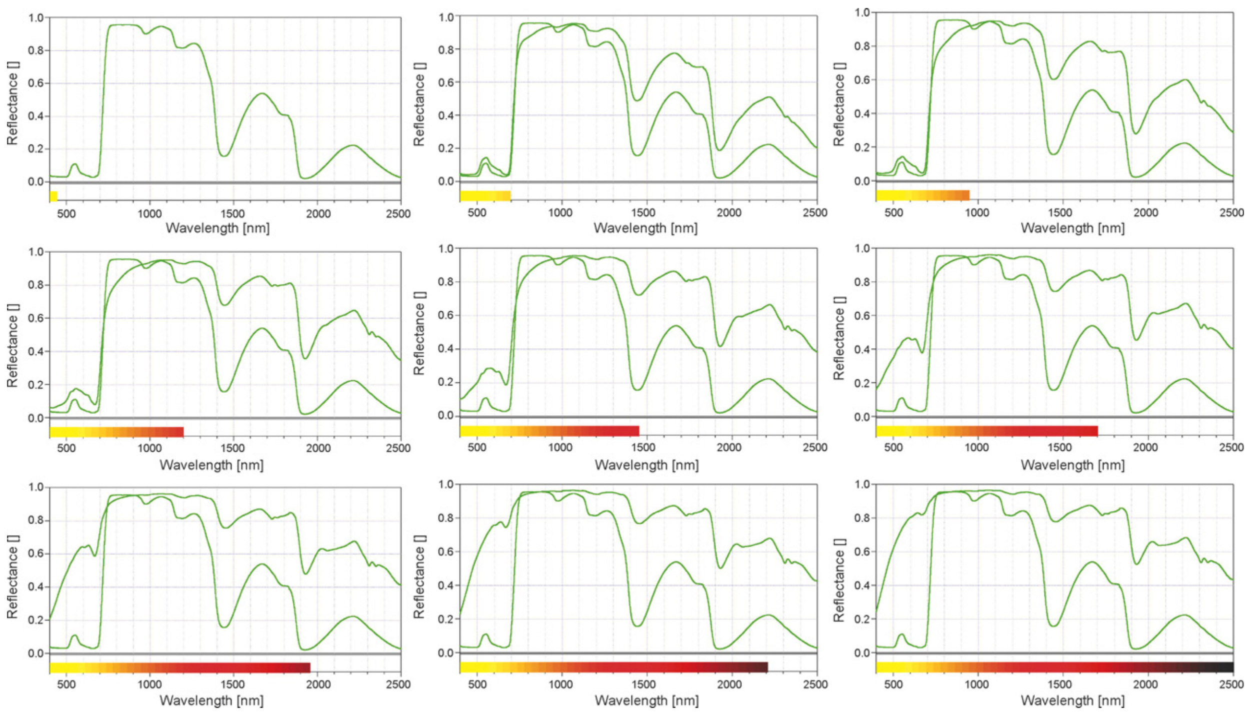

Fig. 15. Measured decay of a '*Ficus benjamina* L.' leaf under laboratory conditions with accelerated (water) stress, induced by illuminating the leaf with a leaf clip using a built-in illumination source. Each image indicates a time step of 55 min with the original, unstressed leaf as a reference (upper left). Total measurement time was 8.3 h (Schaepman and Bartholomeus, 2004).

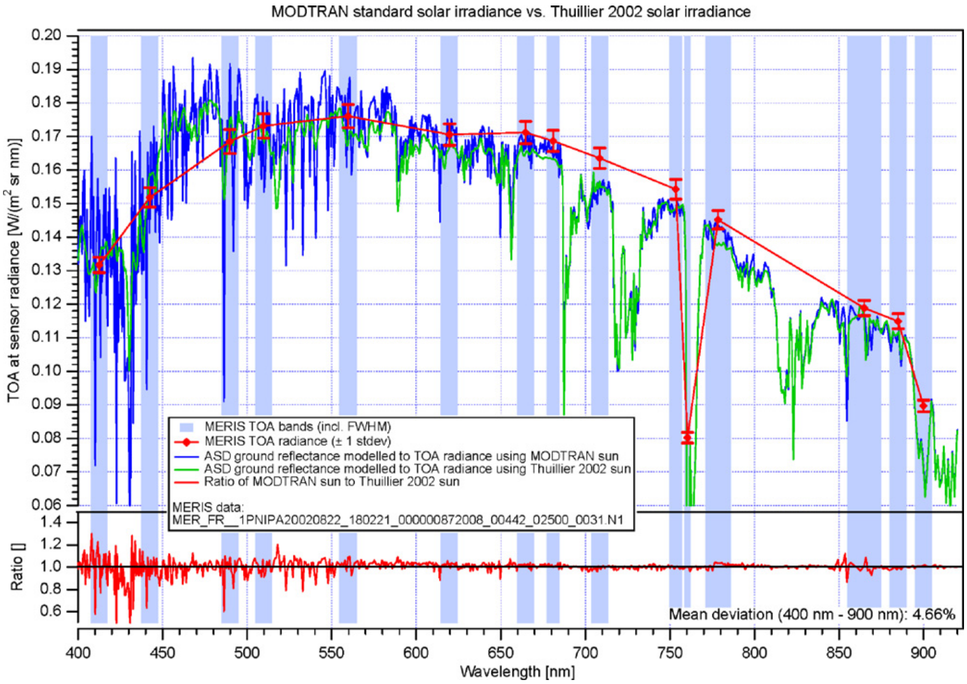

Fig. 16. Top-of-atmosphere (TOA) radiances of MERIS on ENVISAT as modelled using vicarious calibration methods in comparison with two different solar irradiance standards (Kneubühler et al., 2003).

The directional (anisotropic) component is increasingly covered with ground measurement instrumentation (Bruegge et al., 2004; Schoenermark and Roeser, 2004), which are generally referred to as goniometers (Sandmeier, 2000). They exist in various designs, which are represented in Fig. 17.

The general understanding of surface anisotropy and its importance to include in an overall uncertainty evaluation of spectrodirectional-based products has found its general way into the common understanding of processing remotely sensed data. Existing uncertainties can further be minimized by introducing a standardisation of terminology (Schaepman-Strub et al., 2006), as well as carefully evaluating the limitations of spectroradiometric measurements (cf., Fig. 18). But due to the fact that a spectroradiometric measurement is a multidimensional problem – as mentioned already earlier – as well as the inherent instability of the measuring instruments, and the techniques used for eliminating measurement errors, spectroradiometric measurements will remain one of the least reliable of all physical measurements (Kostkowski, 1997)!

The importance of directional research is expressed in two user communities, one of them trying to stress the uniqueness of spectrodirectional images (Barnsley et al., 1994; Gobron et al., 2002; Pinty et al., 2002) whilst retrieving related parameters with increased accuracy, whereas others try to minimize the impact of directionality (Csiszar et al., 2001; Hu et al., 2000;

Fig. 17. Various directional ground acquisition instruments – or so called goniometers. From left: FIGOS (Univ. Zurich, CH), PARABOLA (JPL, USA), ASG (Univ. Colorado, USA), and WAAC (DLR, D) (Bruegge et al., 2004).

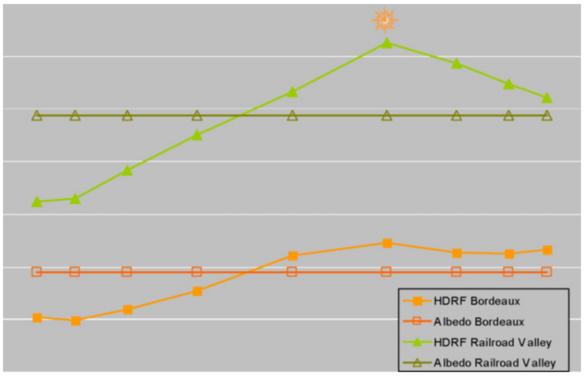

Fig. 18. View angle dependent error of Albedo product retrieval accuracies when ignoring directionality (Schaepman-Strub et al., 2006).

Richter, 1998). Fig. 19 depicts the retrieval difference of directional corrected and non-corrected results expressed in a difference image (Schaepman-Strub et al., 2003). The resulting difference LAI product shows clearly vegetation structure aspects as well as the position of the hot-spot (Li and Strahler, 1992; Liang and Strahler, 1993) as a strong backscattering effect in the irrigated canopies.

Finally, spectrodirectional remote sensing will allow the generation of products that support the estimation of critical vegetation parameters (Rast et al., 2004), but neither is this approach limited to vegetation nor can all relevant parameters be estimated using these sensors alone.

The following table gives an indication of relevant input parameters for land-biosphere modelling as well as the technical implementation concept needed to successfully retrieve them with acceptable uncertainties.

The final products generated using spectrodirectional remote sensing approaches do not differ from any ‘conventional’ retrieval in their final appearance, but significantly differ in the resulting uncertainty. Fig. 20 illustrates classical products, such as LAI (leaf area index), fAPAR (fraction of absorbed photosynthetically active radiation), and fCover (fraction of vegetation cover) as described in the DAISEX experiments in Spain (Berger et al., 2001).

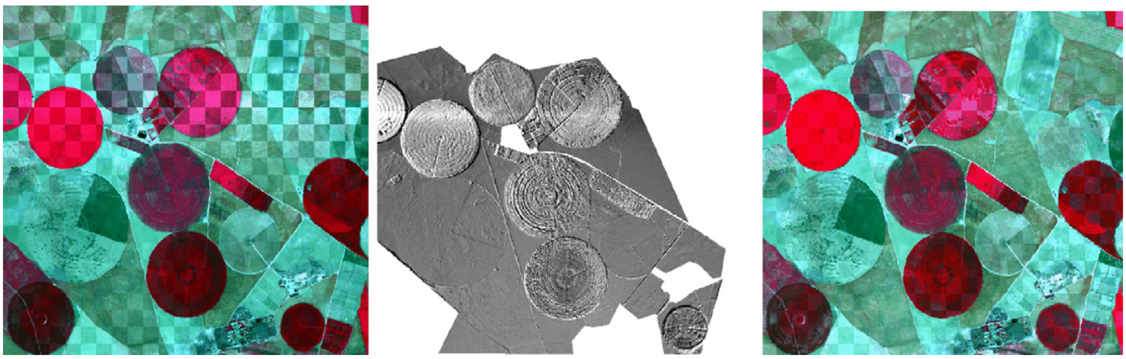

Fig. 19. Vegetation index difference images of directional corrected vs. uncorrected images. *Left*: Directional differences visible in two differently acquired flights. *Right*: Ambrals (Hu et al., 1997) BRDF corrected images, minimizing the directional differences. *Middle*: Difference image of left and right with applied GRVI (green vegetation index, Broge and Leblanc, 2001). Obviously, the difference image in the middle reveals information about the vegetation structure as can be clearly seen (data from Moreno, 2001).

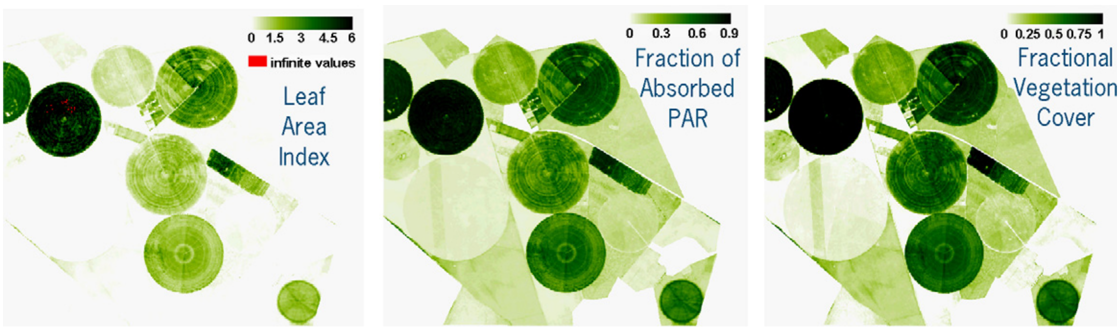

Fig. 20. Three Level 3 products (from left: LAI, fAPAR, and fCover) derived from imaging spectrometers using atmospheric correction, geometric correction, and including a compensation for directional effects induced by the atmosphere and the ground.

2.4. From pixels to processes: the land-biosphere model approach

Typical land-biosphere models are composed of 'building blocks' with associated functions that treat the interaction of photons with vegetation as follows:

- Carbon engine
  - o *f* (CO_2, light, water availability, temperature, nutrients)
- Carbon allocation
  - o *f* (geometry, physiology, plant functional type, species)
- "Remineralisation"
  - o *f* (plant functional type, physiology, microbiology, molecular structure (e.g., lignin versus waxes or cellulose))
- Soil hydrology
  - o *f* (root depth)
- Population dynamics
  - o Succession
    - *f* (stand height, stand age, physiology)
  - o Disturbances
    - *f* (climate, fire, humans)

The *Carbon engine* usually defines how much carbon is fixed per unit time by photosynthesis. In general, the amount of carbon fixed per unit time is a function of ambient (atmospheric) CO_2, light, water availability, temperature, and nutrients. The second part deals with a recipe for *carbon allocation* of carbon fixed by photosynthesis to different living tissue like stems or roots. Carbon allocation is a function of plant geometry and physiology. This is followed by a description of the fate of dead plant material (*Remineralisation*), i.e., the carbon flow from living to non-living forms and its subsequent decomposition. The decay processes are a function of plant species, physiology, microbiology and molecular structure of plant tissue (e.g., lignin versus waxes or cellulose). Next, a predictive equation of soil moisture (*Soil hydrology*) is given. Soil moisture is a function of soil hydraulic properties, evapotranspiration, and precipitation. And finally a representation is given of the dominant stochastic *Population dynamics* processes like early versus late successional species through competition for resources (light, nutrients, water) which is a function of stand height, stand age, and physiology, and disturbance by humans (land use), fire, windfall, insects which is a function of climate and human activity (Gloor, 2005).

Land-biosphere models can be grouped into two broad classes. The ones that use satellite data to locate the "photosynthetically active" land vegetation. In these models, the "Carbon engine" is then driven by absorbed light estimated from satellite and a prescribed light use efficiency. Typical representatives are the CASA model (Potter, 1993) and the TURC model (Ruimy et al., 1996). Population dynamics is in a sense implicit in this

Table 1
Four relevant vegetation parameter blocks needed to successfully run a land-biosphere model and associated remote sensing acquisition concepts

Vegetation variables (parameters)	Spectrodirectional (reflected)	Spectrodirectional (emitted)	Radar (SAR)	Laser (LIDAR)
Vegetation spatial distribution and phenology				
Fractional vegetation cover (fCover)				
Leaf area index (LAI)	✓		✓	✓
Fraction living/dead biomass				
Canopy structure				
Vegetation height				
Vegetation interaction with radiation				
Albedo				
Fraction of absorbed photosynthetically active radiation (fAPAR)	✓	✓		
Foliage chemistry and water status				
Leaf chlorophyll				
Leaf water content	✓			
Leaf dry matter				
Leaf nitrogen/foliage nitrogen				
Vegetation and soil energy balance				
Foliage temperature (related to stomatal evaporation rate)		✓		
Soil temperature (related to water stress)				

formulation as explained later on. The second class of models predicts the spatial vegetation distribution and the organic soil pools on its own, while hydraulic properties of the soils are prescribed. Typical examples are the Lund–Potsdam–Jena (LPJ) model (Sitch et al., 2003), and the Ecosystem Demography (ED) model (Moorcroft et al., 2001). Several models include population dynamic processes like fire disturbance (e.g., LPJ). Nonetheless, only a model that includes the description of demographics (age distribution of species classes as a function of time) and competition for light by including a description of height distribution can properly describe disturbance processes and their effect on land vegetation (Table 1). The only model that currently propagates both height and age distributions is ED.

Table 2 compares five different land-biosphere models indicating their implementation of the building blocks (modified following Gloor, 2005; Schaepman, 2005). A more detailed discussion can be found in the literature (Cramer et al., 1999; Ruimy et al., 1999). Relevant remote sensing observations are used in the building blocks 'Carbon Engine', 'Phenology', and 'Discretization'.

3. Observations by data acquisition systems

In remote sensing, there are several mission categories described, that contribute to the systematic measurement of the Earth's reflected radiance (Fig. 21). These categories include exploratory missions (e.g., ESA: SPECTRA (Rast et al., 2004); NASA: ESSP (Earth System Science Pathfinder Missions, cf., Crisp and Johnson, 2005) and AVIRIS (Green et al., 1998)), technology demonstrators and operational precursor missions (e.g., ESA: CHRIS/PROBA (Cutter et al., 2004) and APEX (Schaepman et al., 2004); NASA: Hyperion/EO-1 (Ungar et al., 2003)), systematic measurement missions (e.g., ESA: MERIS/ENVISAT (Bezy et al., 1999); NASA: MODIS (Myneni et al., 2002)), as well as operational missions (e.g., ESA: MSG-1 (Borde et al., 2004); NOAA: AVHRR (Rao and Chen, 1999)).

Several international programmes and national space agencies and various national initiatives worldwide are developing missions in the above framework. With a particular European focus, the most important to be mentioned is the Living Planet Programme of ESA

Table 2
Comparison of five land-biosphere models describing individual functionality of their core parts ((P)FT—(Plant) functional type; C-ass—carbon assimilation; N—nitrogen; P—phosphorus) (Gloor, 2005; Schaepman, 2005; Knorr, 2000; Wamelink et al., 2000; Anderson et al., 2004; Aber and Federer, 1992)

Model / *Building Block*	**CASA**	**BETHY**	**PnET**	**LM3**	**SMART/SUMO**
Carbon Engine	Light use efficiency, PAR, fPAR	(Farquhar *et al.*, 1982) or LUE	Pmax=a+b*N, where N is foliar nitrogen	(Farquhar *et al.*, 1982)	C-ass = f(light, N,P,water availability, temp)
Phenology	fPAR	?	Predicted	fPAR	Not relevant (timestep = 1y)
Allocation	Globally fixed ratios; leaf, litter, roots	?	Simple allocation rules for tissue types	Allometries	Ratios (root, shoot, leaf) fixed per vegetation type
Remineralisation	5 litter, 2 organic pools, first order decay	?	No soil carbon component	Fast and slow pools of C and N	Litter + 2 organic pools, fixed ratio + 1st order decay
(Soil-) Hydrology	Bucket type	Bucket type	One soil layer	Bucket type	Supplied by external hydrological model (WATBAL, SWAP)
Discretization	PFT's	PFT's	Biomass produced only by tissue type (foliage)	Defined by mortality and fecundity functions (species build a continuum)	5 FT's that compete for light, N, P, water
Demography	None	None	None	Core of model	None (but tree mortality included)
Reference	(Potter, 1993)	(Knorr, 2000)	(Aber & Federer, 1992)	(Anderson *et al.*, 2004)	(Wamelink *et al.*, 2000)

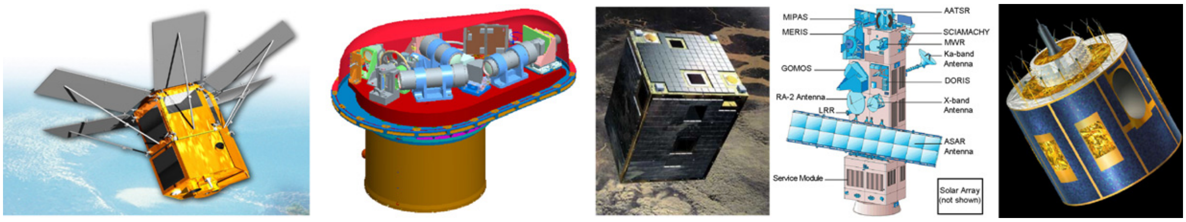

Fig. 21. Current and future remote sensing missions can be subdivided into the following categories: exploratory missions, technology demonstrators (or operational precursor missions), systematic measurement missions, and operational missions (from left: SPECTRA, APEX, CHRIS, ENVISAT, and MSG).

(Readings, 1998), composed out of two major elements: (i) a science and research element in the form of the Earth Explorer missions (e.g., Earth Explorer missions approved so far are: CryoSat (determines variations in the thickness of the Earth's continental ice sheets and marine ice cover, but CryoSat was lost due to a launch failure on October 8, 2005), GOCE (Gravity Field and Steady State Ocean Circulation Explorer), ADM-Aeolus (Atmospheric Dynamics Mission), SMOS (Soil Moisture and Ocean Salinity), Swarm (Dynamics of the magnetic field), and EarthCARE (Earth Clouds, Aerosols, and Radiation Mission) and (ii) an element designed to facilitate the delivery of Earth observation data for the eventual use in operational services. This includes the well-established meteorological missions with the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) and also new missions focusing on the environment and civil security. This latter element, which is a joint initiative between the European Commission and ESA, is called GMES (GMES—Global Monitoring for Environment and Security: an initiative to secure Europe with an autonomous and operational information production system in support to environment and security policies). The space component of GMES includes the development and operations of all satellite and ground segment infrastructure providing the required data streams for the Sentinels (these are: Sentinel 1—C-band SAR; 2—Superspectral; 3—Operational Oceanography and Land Surface Mission (Altimeter plus spectrometer); 4/5—Atmospheric Chemistry (Geostationary, low Earth orbit)).

In particular, the first element, the Earth Explorer component, promises to launch five missions during the next 6 years (2005–2011). These are complementing existing missions, but also contribute significantly to enhanced understanding of the Earth System, adding a unique contribution to the international Earth observation capabilities (Schaepman et al., 2005a).

4. Trends—integrated systems solutions and in situ sensing

Historically, remote sensing and GIS needed to be integrated, because they pursued different and separate tracks. Integration of GIS and Remote Sensing was a keyword in Geo-Information Science in the 1980s and 1990s. At this time it sounded like people dealing with vector and raster representation of data needed further integration. But today we are looking at much more elaborated systems, namely integrated systems solutions supporting data assimilation. These solutions will provide scalable approaches, allowing the integration of multiple data sources. They also represent collaborative environments, supporting quantitative data analysis at several scales. Data assimilation will further allow the solid coupling of physical models, linking soil–vegetation–atmosphere transfer (SVAT) models to state space estimation algorithms (e.g., Kalman filters) (Choudhury, 2001; Crow and Wood, 2003; Houser et al., 1998; Olioso et al., 1999; Weiss et al., 2001).

Remote sensing will be increasingly part of a multidisciplinary research environment, complemented by in situ sensing. The latter will be a technology that is used to acquire information about an object, where the distance between the object and the sensor is comparable small to any linear dimension of the sensor (sensing in place). Networks of in situ sensors exist already for a while (e.g., meteorological stations), and it's becoming increasingly feasible to provide telecommunication technologies with these networks to achieve (near) real time integration of heterogeneous sensor webs into the information infrastructure (Bacharach, 2005; Chien et al., 2005).

5. Current achievements and outlook

Spectrodirectional remote sensing enables biophysical and biochemical variables of the Earth's surface to be mapped with unprecedented accuracy. In addition to this, our quantitative understanding of the photon–vegetation interaction has been significantly deepened, by looking at many, contiguous spectral bands, as well as various view-angles to the Earth' surface.

Practically, this particular success is based on improved data quality and wider availability of consistent remote sensing observations to the user community. Secondly, it is due to the broader availability of computing resources, that are needed to run quantitative, physical-based models.

In the near future, new emerging applications in spectrodirectional remote sensing of vegetation will focus on monitoring transitional zones, and in particular ecotones, e.g., ecosystem-, communities-, or habitat boundaries (e.g., tundra-boreal forest, forest-heathland, etc.), where most of the pressure and changes in terms of disturbance are being identified, also managed ecosystems, where precision appliance is a key economical factor, contributing to better yield estimates, and finally (un-)managed ecosystems, where plant succession, plant functional types, and invasive species are important focus areas.

The above will be complemented by the consistent measurements of calibrated and validated surface reflectance to derive Albedo products, retrieval of columnar atmospheric absorption, such as water vapour and aerosol particle size distribution, the fraction of vegetation contributing to the photosynthetic processes, separation of canopy water and atmospheric water content, the canopy light use efficiency (LUE) for estimation of the carbon fixation rates, fire fuel and fuel moisture, as well as anthropogenic and non-anthropogenic induced disturbance (Asner et al., 2005; Stuffler et al., 2004).

Major challenges to be resolved with spectrodirectional remote sensing is still a continuous potential mismatch of spatio-temporal scales of field, airborne and spaceborne measurements, and model requirements. These must be addressed by pursuing a rigorous scientific agenda that is not limited to the scientific use of spectrodirectional data, but also includes a more thorough view on spatio-temporal discontinuities in measurements that may result in variable data and product quality, disturbance processes that are difficult to capture, due to limited mission duration times and missing backward compatibility, data assimilation schemes becoming more important due to the steadily increasing availability of geo-data at large, and finally there will be a convergence to Earth System Sciences observed, truly linking various disciplines into multidisciplinary approaches.

The combination of coupled soil–vegetation–atmosphere transfer in view of ecological and CO_2 related research questions will be – as demonstrated in this short overview – a primary focus for the upcoming years.

Regional environmental modelling using spectro-directional remote sensing will allow a more consistent understanding of the relevant processes of our system Earth.

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